Renewable and Sustainable Energy Reviews 15 (2011) 4156–4170

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Advances in liquid based photovoltaic/thermal (PV/T) collectors

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ARTICLE INFO

Article history:
Received 7 January 2011
Accepted 5 July 2011
Available online 16 September 2011

Keywords:
Hybrid photovoltaic/thermal (PV/T)
Heat pump
Refrigerant
Evaporator–collector
Heat and electricity conversion
Exergy
Performance

ABSTRACT

In order to get more power and heat from PV/T system, it is necessary to cool the PV cell and decrease its temperature. This is not an easy task especially in hot and humid climate areas. There is a lack of an effective cooling strategy of PV/T panels. The liquid based photovoltaic thermal collector systems are practically more desirable and effective than air based systems. Temperature fluctuation in liquid based PV/T is much less than the air based PV/T collectors which subjected to variation in solar radiation levels. In this study a review of the available literature on PV/T collector systems which utilize water and refrigerant (working fluid) as heat removal medium for different applications has been conducted. Future direction of water-cooled and refrigerant hybrid photovoltaic thermal systems was presented. This study revealed that the direct expansion solar-assisted heat pump system achieved better cooling effect of the PV/T collector.

Contents

1. Introduction

The advent of the oil crisis in the early 1970s and the global environmental concerns in the nineties forced many to look for alternative renewable and clean energy sources. Therefore, there is a need to develop an ingenious method of solar energy conversion systems and then to substitute it where applications of fossil fuels are most vulnerable. Biomass, solar energy and wind energy for instants are the world's most abundant permanent source of energy and are also important and environmentally compatible sources of renewable energy [1,2].

The application of solar energy can be broadly classified into two categories; thermal energy systems which converts solar energy into thermal energy and photovoltaic energy system which con-

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doi:10.1016/j.rser.2011.07.028

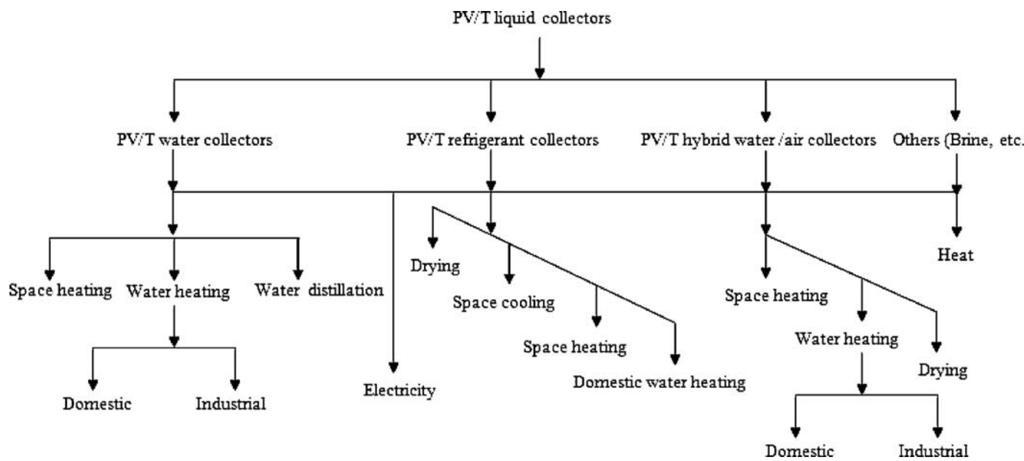


Fig. 1. A classification of PV/T liquid based collectors.

verts solar energy into electrical energy. The vital component in solar energy system is the solar collections systems. Two solar energy collection systems commonly used are the flat plate collectors and photovoltaic cells. Normally, these two collection systems are used separately. These two systems can be combined together in a hybrid photovoltaic thermal (PVT) energy system. The term PVT refers to solar thermal collectors that use PV cells as an integral part of the absorber plate. The system generates both thermal and electrical energy simultaneously. The number of the photovoltaic cells in the system can be adjusted according to the local load demands. In conventional solar thermal system, external electrical energy is required to circulate the working fluid through the system. The need for an external electrical source can be eliminated by using this hybrid system. With a suitable design, one can produce a self-sufficient solar collector system that required no external electrical energy to run the system [3]. Photovoltaic (PV) modules convert a part of solar radiation energy directly into electricity, while, the unconverted part of the solar radiation into electricity is absorbed in a PV module resulting in very high temperatures [4]. The photovoltaic (PV) cells suffer efficiency drop as their operating temperature increases especially under high insulation levels and that in order to maintain a high electrical output from the PV device, the operation temperature of the PV/T system needs to be kept low [5–7].

The collector is attractive for solar energy applications in which limited space and installation cost are of primary concern [8]. The different options in the development in PVT systems have been categorized by the heat transfer fluid used, i.e. air, water, refrigerant. The choice of the heat transfer fluid is important to the design of PVT systems [3]. Natural or forced air circulations are simple and low cost methods to remove heat from PV modules, but they are less effective if the ambient air temperature is over 20 °C [9]. To overcome this effect, the heat can be extracted by circulating water through the collector. A water-based PV/T system is able to achieve a higher overall energy output per unit collector area than the "side-by-side" systems. However, for daily operation, the photovoltaic efficiency of the hybrid system still will drop considerably towards the end of the day, when the heat removal fluid (water) temperature in the storage tank will finally reach the level that meets the hot-water demand requirements. If the evaporating refrigerant of a heat pump is used as the coolant of the PV cells, the operating temperature would be lower and a higher PV efficiency can be achieved [10].

The objectives of this paper are to review the refrigerant and water type PV/T collectors amongst the PV/T liquid type collectors and identify the research needs in these areas. In addition, future research directions and needs have been identified and elaborated.

2. Classification of PV/T liquid collectors

The most common working fluid in liquid based PV/T collectors are water, water/air and most recently refrigerant. The water type PV/T collectors are the most widely system studied. Classification scheme for PV/T liquid collectors is given in Fig. 1.

3. Refrigerant based PV/T collectors

Photovoltaic and solar-assisted heat pumps are two different technologies. A photovoltaic (PV) system consists of interconnected solar cells which convert photons directly into electron flow. A direct expansion solar-assisted heat pump system (DXSAHP) directly integrates Rankine refrigeration device with solar thermal collector. The solar collector serves as an evaporator where the refrigerant absorbs thermal energy from solar radiation [11].

It is a well-known fact that the electricity generating efficiency of solar cells drops with the increase in operating temperature. A photovoltaic/thermal (PV/T) system, which applies a coolant onto the solar cells, can override such a limitation by bringing down its operating temperature and re-utilizing the captured heat energy. The refrigerant as the working fluid at the solar collector undergoes phase change at a relatively low temperature. The energy conversion efficiency is therefore improved [10]. The higher evaporating temperature of refrigerant at the evaporator–collector owing to the solar heating effect. This increases the coefficient of performance (COP) of the heat pump.

For heat pumps, a basic factor of great importance for its successful application is the availability of a cheap, dependable heat source for the evaporator—preferably one at relatively high temperature. The coefficients of performance (COP) of heat pump systems depend on many factors, such as the temperature of the low-energy source, the temperature of delivered useful heat, the working medium used and the characteristics of components of heat pump systems. However, amongst these factors, the temperature of the evaporator is the key factor.

In order to improve the COP of heat pump and efficiency of the collector and displace the fossil energy resource, the idea of combining the heat pump and solar energy in mutual beneficial ways has been proposed and developed by several researchers [12].

3.1. Experimental work

A PV/T heat pump system has been constructed and experimental studies have been conducted. The coefficient of performance of the system was higher than 6 when the condenser supply water temperature was 40 °C [13].

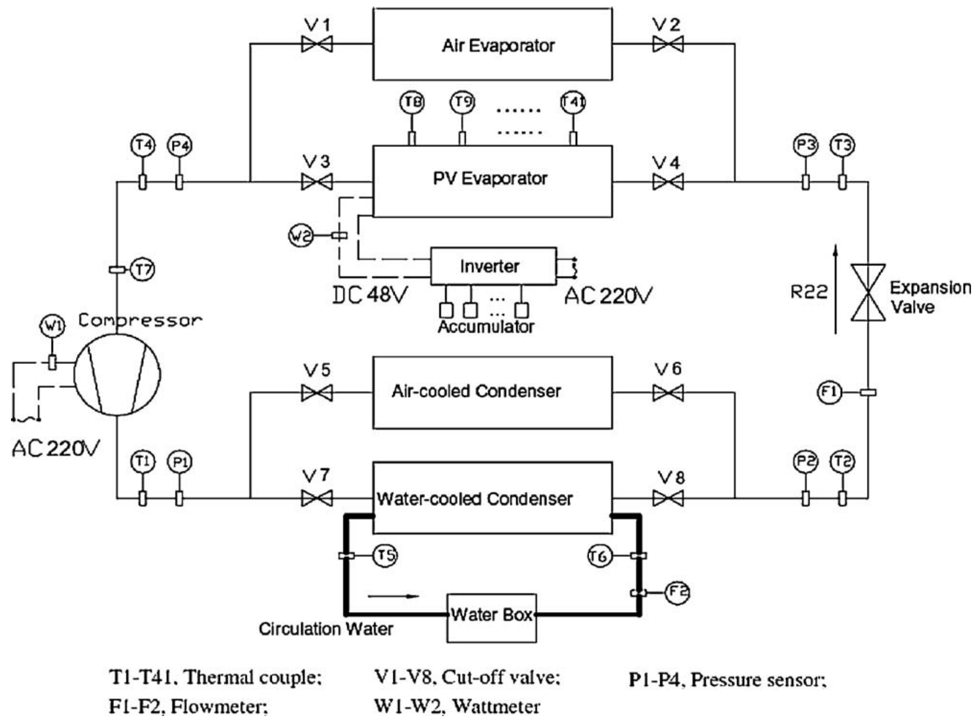


Fig. 2. Schematic diagram of the PV-SAHP experimental set-up [10,11,16].

A novel photovoltaic solar assisted heat pump using R22 has been studied (Fig. 2) [10]. Four different operating modes with distinctive condenser supply water temperatures of 20 °C, 30 °C, 40 °C and 50 °C has been proposed in this study. The results for the photovoltaic solar assisted heat pump (PV-SAHP) system indicated that:

1. A higher supply water temperature leads to a higher compressor input power. The daily average compressor powers are determined as 238 W, 316 W, 422 W and 552 W for the water temperatures at the condenser inlet (T_{win}) of 20 °C, 30 °C, 40 °C and 50 °C, respectively.
2. the average COP of heat pump were found to be 7.1, 6.6, 4.4 and 3.5 at T_{win} of 20 °C, 30 °C, 40 °C and 50 °C, respectively.
3. The average photovoltaic powers were found as 381 W, 393 W, 375 W and 343 W corresponding to T_{win} of 20 °C, 30 °C, 40 °C and 50 °C.
4. The max COP, max $COP_{p/t}$, average COP, average $COP_{p/t}$, and average photovoltaic efficiency were 10.4, 16.1, 5.4, 8.3, and 13.4%, respectively. These indicate that the thermal performance of the proposed PV-SAHP system is better than the conventional heat pump systems and at the same time, the photovoltaic efficiency is also improved.
5. The PV-SAHP system has a superior coefficient of performance (COP) than the conventional heat pump system and with higher photovoltaic efficiency. The COP of the heat pump was able to reach 10.4 and the average value was about 5.4. The average photovoltaic efficiency was around 13.4%. The highest overall coefficient of performance ($COP_{p/t}$), taking into consideration both the photovoltaic and thermal efficiency, was about 16.1.

3.2. Simulation studies

A mathematical model based on the distributed parameter technique was used for predicting the dynamic system behavior. Corresponding experiment carried out to determine the actual performance and to verify the numerical model. The PV efficiency was found above 12%, which is higher than the performance in the other types of PV/T system. Hence, better cooling effect of the PV cells have been achieved. Simulation results, such as temperature, electrical output and heat gain show satisfactory agreement with the experimental data. The deviations of the predicted and measured output electricity and PV efficiency were within ±8%. The mean absolute deviations of the heat gain and thermal efficiency were about 10%. However, the model underestimates the refrigerant pressure drop at the PV evaporator [11].

The performance of a photovoltaic solar assisted heat pump (PV-SAHP) with variable-frequency compressor reported in Tibet [14]. The solar collectors extract the required thermal energy from the heat pump and at the same time, the cooling effect of the refrigerant lowers the working temperature of the solar cells. Hence, this combined system has a relatively high thermal performance with an improved photovoltaic efficiency. To adapt to the continuously intermittent nature of solar radiation and ambient temperature conditions, the refrigerant mass flow rate should match the heat gain at the evaporator accordingly. A variable frequency compressor and an electricity-operated expansion valve were used in the proposed system. Mathematical models were developed to evaluate the energy performance of the combined system based on the weather conditions of Tibet. The simulation results indicated that on a typical sunny winter day with light breeze, the average COP could reach 6.01, and the average electricity efficiency, thermal efficiency and overall efficiencies were 0.135, 0.479 and 0.625, respectively.

A photovoltaic/thermal panel and a ground coupled heat pump (Fig. 3) have been simulated using TRNSYS [15]. The system consisting of a ground coupled heat pump and 25 m^2 of unglazed PVT panels was able to satisfy 100% of the total heat demand for a typical newly-built Dutch one-family dwelling. It is able to generate nearly all of its own electricity use and keeping the long-term average ground temperature constant. The electrical and thermal yield of this reference system and the total investment is equal to that of the PVT system, as well as the net heat extraction.

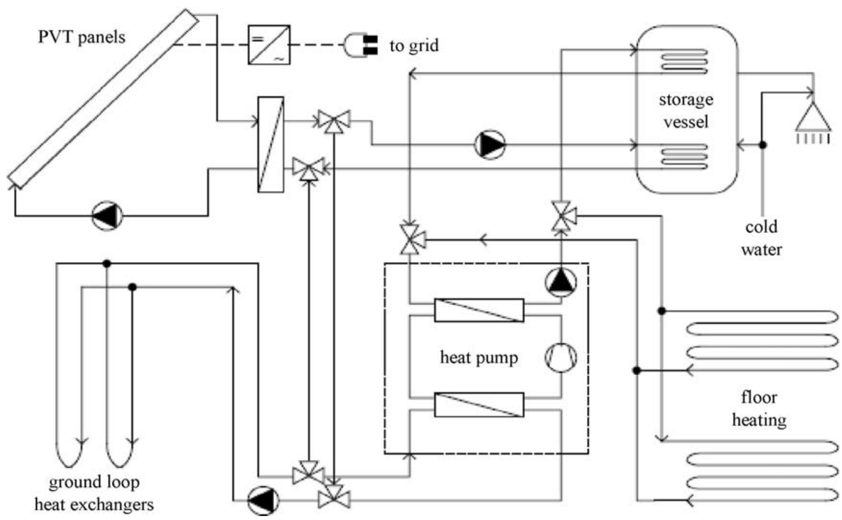


Fig. 3. Schematic overview of the system [15].

Numerical studies of the PV/T heat pump system as shown earlier in Fig. 2 have been conducted [16]. The simulation showed that this system enhanced the PV-efficiency by 16% higher than that of conventional PV system and COP of this system was about 43% higher than that of the conventional heat pump. The overall PV/T efficiency of 84.7% can be achieved by the PV/T-SAHP system.

A photovoltaic/thermal heat pump (PV/T-HP) system (Fig. 4) having a modified collector/evaporator (C/E) has been developed and the simulation studies have been conducted [17]. Multi-port flat extruded aluminum tubes were used in the modified C/E, as oppose to round copper tubes used in a conventional C/E. This proposed PV/T-HP system was promising for electricity generation, domestic hot water heating and space heating. The simulation results of the system's performances when operated for water heating under a typical weather condition of in summer showed that the new PV/T-HP system having the modified C/E achieved a higher COP by 7%, a higher thermal efficiency by 6% and a relative electrical efficiency coefficient by 2%, compared to those of the PV/T-HP system having a conventional C/E. The simulation results also suggested that the new PV/T-HP system with the modified C/E could efficiently generate electricity and heating 150 L water up to 50 °C all-year-round in both Nanjing and Hong Kong, China. When compressor speed was controlled at three different levels in different seasons, system's COPs improved significantly in summer months, and heat outputs, increased and meet most of the required heating load in winter months.

A direct expansion PV/T heat pump system (Fig. 5) was designed [18]. Mathematical model has been developed to analyze the complex energy conversion processes. Numerical simulation was then performed based on the distributed parameters approach. An experimental rig was also built to verify the real performance of the system as compared to the simulation model prediction. The results indicated that this photovoltaic solar assisted heat pump (PV-SAHP) has better coefficient of performance (COP) and photovoltaic efficiency than the separate units. Under the experimental conditions, the COP of the PV-SAHP reached 8.4 and the average value was around 6.5, whereas the average photovoltaic efficiency was around 13.4%. The experimental results were found in good agreement with the theoretical predictions on the system responses with changes environmental conditions.

The performance of PV/T evaporator of a PV/T solar collector studied theoretically and experimentally for some years [19]. The results showed that the PV/T evaporator had an overall efficiency in the range of 0.64–0.87, thermal efficiency 0.53–0.64 and PV efficiency 0.124–0.135. In order to test the real performance of the system an experimental rig was built and the experiment measurements were found in good agreement with the simulation results.

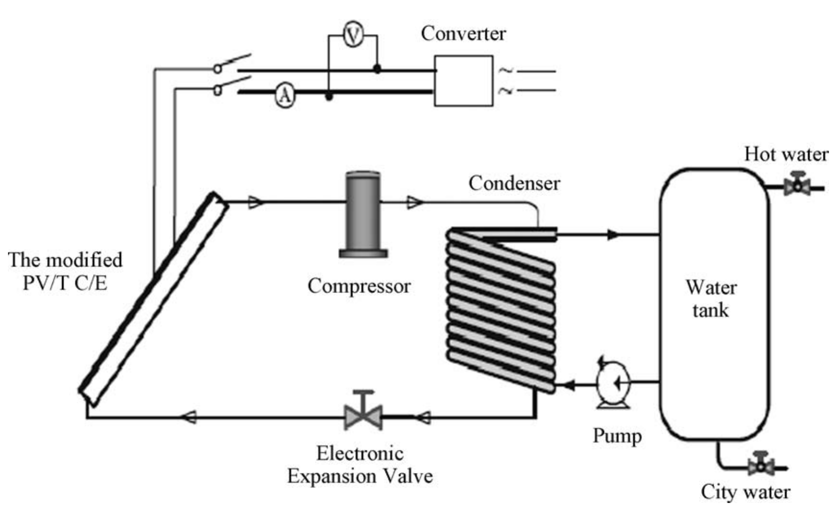


Fig. 4. The schematic diagram of the new PV/T-HP system. [17].

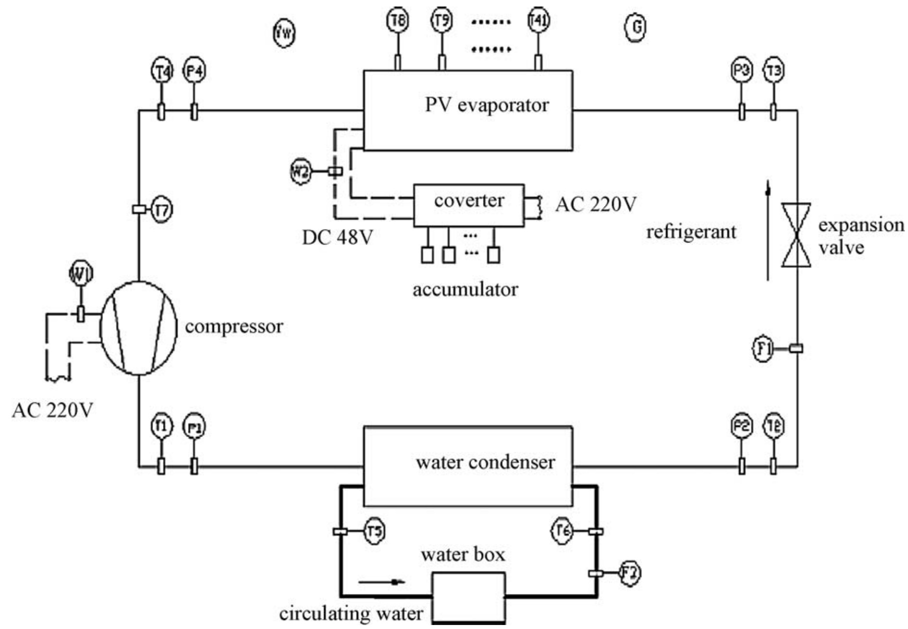


Fig. 5. Outline schematic diagram of the experiment rig (*Note:* T1–T41: Thermocouple; P1–P4: Pressure sensor; F1–F2: Flowmeter; W1–W2: Wattmeter; G: Pyranometer; Vw: Anemometer) [18,19].

4. PV/T water collectors

Water, air or refrigerant can be used as the heat removal media to cool the solar cells. The water is convenient not only because of its high thermal capacity, but also due to its optical properties [20]. Water absorbs light mainly in the infrared region and thus is compatible with PV modules using shorter wavelengths in the solar radiation spectra for its conversion to electricity [21].

4.1. Performance of collectors

Many factors affect performance of a photovoltaic installation, such as shading, dust accumulation, fallen objects on solar panels, corroded connections, component failure in inverter or solar modules, etc. The occurrence of these factors will result in under-performance of a PV system; hence affect the financial and environmental returns on investment. Few installations come with web monitoring service; resulting in, most under-performing systems go undetected [22].

A number of parameters have been identified to affect PV/T performance. These include mass flow rate, inlet temperature of working fluid, number of covers, absorber to fluid thermal conductance [29], cell density, collector length, duct depth [30] and in the case of water type PV/T collectors, absorber plate design parameters such as tube spacing, tube diameter and fin thickness. Table 1 summarizes some of selected types of cells for PVT applications. It also shows, those specifications of system and absorber plate which influence the system performance. In this work, the effects of environmental parameters have not been presented.

4.1.1. Simulation work

A combined thermal and photovoltaic solar energy collector was successfully constructed by pasting single-crystal silicon cells onto a black, plastic, heat absorber. The adhesive was sufficiently elastic to absorb the difference in thermal expansion between the cells and the absorber. An analytical model of the PV/T system, the temperature development profile of the system, and photovoltaic and thermal performance presented. The simulation results were in agreement with the experimental data [25].

Table 1
Summary of some selected studies of influencing parameters on system performance.

Type of cells	Mass flow rate (kg/s)	Water inlet temperature (°C)	No. of covers	$F_R(\tau\alpha)n$	F_RU_L	Tube (m)		Fin thickness	Average irradiation (W/m^2)	Ambient temperature (°C)	Ref.
						Spacing	Diameter				
Pc-Si and a-Si	0.02	N.A.	1	N.A.	N.A.	N.A.	N.A.	N.A.	1317.2–1749.1 (kW h/m^2)	7.9–18.5	[5]
Monocrystalline	300 ml/min	24–27	1	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	[19,20]
Polycrystalline	N.A.	25.4–35.3	1	N.A.	N.A.	N.A.	N.A.	N.A.	6.6–15.9 (MJ/m^2 day)	25.4–29.6	[23]
Multi-crystalline silicon	N.A.	N.A.				N.A.	N.A.	N.A.	N.A.	N.A.	[24]
Single-crystal silicon	N.A.	10–12	0 1	0.72–0.79 0.7–0.72	11–17.4 8.1–8.5	N.A.	N.A.	N.A.	749	8–9	[25]
Multi-crystalline	76 kg/m h	N.A.	0-2	N.A.	N.A.	0.09	0.01	N.A.	800	20	[26]
Crystalline silicon	2 l/m	N.A.	0 1	0.44–0.47	18.7 5.1	0.23	0.008	N.A.	N.A.	20	[27]
N.A.	0.38 kg/s m^2	20	1	0.61	5.43	0.095	0.01	N.A.	133.59–152.02 (kW h/m^2)	20	[28]

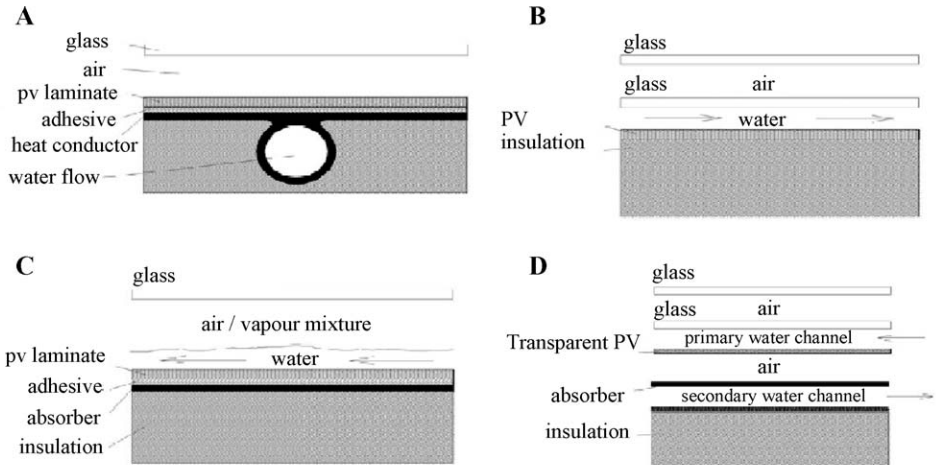


Fig. 6. Various collector concepts: (A) sheet-and-tube PVT, (B) channel PVT, (C) free flow PVT, (D) two-absorber PVT (insulated type) [26].

An analytical expression for characteristic equation of combined system of photovoltaic thermal (PV/T) flat plate collectors derived for different condition as a function of design and climatic parameters and experimentally validated for various configurations [31]. The results indicated that there was a significant increase in the instantaneous efficiency from 33% to 64% from case A (The absorber was fully covered by photovoltaic (PV) glass to glass module) to case C (The absorber was partially (30.56%) covered by photovoltaic (PV) module and connected in series with conventional collector) due to increase in glazing area.

Numerical analysis for nine design concepts of water-type PVT-collectors which classified in four groups (Fig. 6) indicated that the thermal and electrical efficiencies at zero reduced temperature for [26]:

1. Sheet and tube PVT-collector 0, 1 and 2 covers were 52%,58%58%, 9.7%, 8.9% and 8.1%, respectively.
2. PVT-collector with channel above PV, below opaque PV and below transparent PV was 65%, 60%63%, 8.4%, 9% and 9%, respectively.
3. Free flow PVT-collector was 64% and 8.6%, respectively.
4. Two-absorber PVT-collector insulated type and non-insulated types were 66%, 65%, 8.5%and 8.4%, respectively.

Based on the control-volume finite-difference approach, an explicit dynamic model was developed for a single-glazed flat-plate water-heating PV/T collector [32]. A transport delay fluid flow model was incorporated. The proposed model was suitable for dynamic system simulation applications. It allowed detailed analysis of the transient energy flow across various collector components and captures the instantaneous energy outputs.

A numerical model of a photovoltaic–thermosyphon collector with rectangular flow channels was developed and the model accuracy was verified by comparison with measured data [33]. The energy performance of the collector system was then examined first, through reduced-temperature analysis, and second, as applying in a typical hot summer and cold winter climate zone of China. The numerical results were found very encouraging, and the overall performance of the hybrid collector system was found promising in providing an alternative means of energy source for the domestic sector of China.

A physical model of a hybrid photovoltaic/thermal system proposed and algorithms for making quantitative predictions regarding the performance of the system presented [34]. The model was based on an analysis of energy transfers due to conduction, convection and radiation and predicts the amount of heat that could be drawn from the system as well as the (temperature-dependent) power output. Special emphasis was laid on the dependence of the fin width to tube diameter ratio. The authors proposed a domestic system for the combined production of electricity and low temperature heat (for example as a pre-heater in a hot water system) and a large-scale system that might be interesting regarding production of hydrogen and fresh water as applications.

A hybrid photovoltaic–thermal (PV/T) solar energy system was simulated using TRNSYS and typical meteorological year (TMY) conditions for Nicosia, Cyprus considered [35]. The results showed that the optimum water flow rate of the system was 25 l/h. The hybrid system increased the mean annual efficiency of the PV solar system from 2.8% to 7.7% and in addition covered 49% of the hot water needs of a house, thus increasing the mean annual efficiency of the system to 31.7%. The life cycle savings of the system was Cy£790.00 and the pay-back time was 4.6 years.

A PV/T collector conventional forced circulation type water heater simulated [36]. The simulations did for different solar cell areas, mass flow rates and different water masses. The differential temperature controller, i.e. pump-off and pump-on, used. The pump-on time was more or less independent of the total stagnant water mass in the collector unit. The pump-off time was a sensitive function of the water flow rate. It was shown that a normal domestic solar water heater of about 2 m^2 generated sufficient electrical energy (after taking into account the various losses in storage, etc. and the energy required by the pump) to run 2 tube lights of 20 W each for 5 h and 1 television of 30 W for 4 h.

A polycrystalline (pc-Si) silicon and amorphous silicon (a-Si) photovoltaic/thermal solar cells combined with water heat extraction units constructed and tested at the University of Patras [9]. TRNSYS simulation results for hybrid PV/T solar systems for domestic hot water applications both passive (thermosyphonic) and active presented. The results showed that the electrical production of the system employing polycrystalline solar cells was more than that employing the amorphous ones, but the solar thermal contribution was slightly lower. The derived TRNSYS results gave an account of the energy and cost benefits of the studied PV/T systems with thermosyphon and forced water flow. Thus, the PVs had better chances of success especially when both electricity and hot water was required as in domestic applications.

A dynamic 3D simulation model and tree steady state models which were 1D, 2D and 3D models presented for simulation of the thermal yield of a combined PV–thermal collector and the results of simulation study compared to experimental results [37]. It was found that all models follow the experiments within 5% accuracy. The daily yield was calculated using the simple 1D steady state

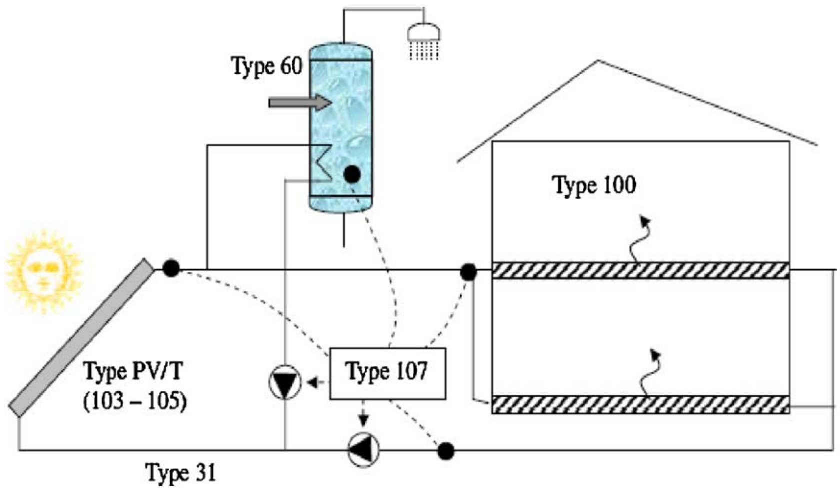


Fig. 7. Diagram of the modeled installation [38].

model, whereas the 2D and 3D models were more adapted to other configurations and provided more detailed information. This study indicated that the time-dependent model was required for an accurate prediction of the collector yield if the collector temperature at the end of a measurement differed from its starting temperature.

The theoretical analysis of PV/T systems for domestic heating and cooling was reported by Vokas et al. [28]. By using the f-chart and f-chart cooling methods, it concluded that the thermal energy produced by PV/T systems may cover remarkable part of the domestic heating and cooling load. The geographical region had important affect on the percentage of the solar coverage of the domestic heating and cooling load.

Water hybrid PV/T collectors applied to combisystems of heating systems and domestic hot water proposed [38]. General diagram of the modeled installation is showed in Fig. 7. The advantage of the direct solar floor (DSF) was that an additional solar tank was not used due to the fact that solar energy was directly stored in the floor. In this study a direct solar floor application had been considered because of its low operating temperature level which was 35 °C maximum and it was likeable for a PV electricity production.

A dynamic simulation model of a building-integrated photovoltaic and water heating system introduced [39]. The results of the simulation model gave very good prediction of the water-heating and wall transmission performance even after successive cycles of heat gains and losses. This dynamic simulation model was therefore proven to be highly useful in predicting the system dynamic behavior as well as the long-term energy performance.

The annual performance of facade-integrated hybrid photovoltaic/hot-water system for use in residential buildings of Hong Kong analyzed using a computational thermal mode [40]. The results of simulation study led to the following conclusions:

(1) The annual electric efficiencies of the hybrid EPV/T and BPV/T systems were 4.3% and 10.3% for a west-facing panel, and the annual overall thermal efficiencies were 58.9% and 70.3%, respectively.
(2) The annual efficiencies of the water heating systems were 47.6% (for EPV) and 43.2% (for BPV), respectively; the corresponding number of days in a year when the water temperature in the storage tank reached 45 °C and above was 195 and 217. The water heating system thus could support most domestic usage and also could serve as a pre-heater of a hot-water system.
(3) Compared with a normal concrete wall, the reduction of space heat gain through the two kinds of hybrid PV/T collector wall could reach 53.0% and 59.2%, respectively.

The thermal and electrical behavior of a wall-mounted solar photovoltaic/thermal collector system through a numerical model was developed by modifying the Hottel–Whillier model [41]. The influences of the mass flow rate and the packing factor on the thermal and electrical performance of the water-type photovoltaic/thermal collector were analyzed. The simulation results showed that the increase of working fluid mass flow rate was beneficial for PV cooling. System operation at the optimum mass flow rate not only could improve the thermal performance of the system, but also could meet the PV cooling requirement so that a better electrical performance could also be achieved.

A dynamic system model for a PV/T water heating system was developed [42]. The effects of PV cell covering factor and glazing transmissivity had been evaluated. The simulation results based on the validated dynamic model indicated that the higher the covering factor and the glazing transmissivity, the better the overall performance.

4.1.2. Experimental work

An integral-type solar system (IPVTS) made using a commercial polycrystalline PV module [23]. The test results showed that the solar PV/T collector could obtain a good thermal efficiency. The primary-energy saving efficiency of this IPVTS exceeded 0.60. This was higher than for a pure solar hot water heater or a pure PV system. The performance of a PV/T collector could be improved if the heat-collecting plate, the PV cells and the glass cover were directly packed together to form a glazed collector. The manufacturing cost of the PV/T collector and the system cost of the IPVTS could also be reduced. The present study showed that the idea of IPVTS was economically feasible too.

A new Integrated Solar Home System (Fig. 8) which utilize PV module introduced [24,43]. This eased installation and reduced costs and failures. Additionally, through the integration of a water tank that serves as a cooling unit as well as the system foundation, a significant reduction of operating cell temperature was achieved, increasing electrical yield by 9–12%. It was also capable of supplying the hot water needed for a small household.

A polymer solar heat collector was combined with single-crystal silicon PV cells in a hybrid energy-generating unit that simultaneously produced low temperature heat and electricity proposed

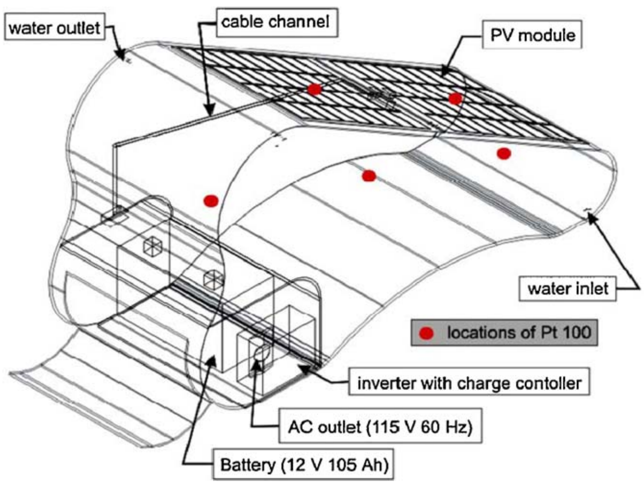


Fig. 8. Structure and components of the Integrated Solar Home System (I-SHS) [24,43].

[25]. The PV/T unit was tested experimentally and thermal efficiency measurements for different collector configurations were compared, and PV performance and temperature readings were presented and discussed.

The result of experimental study of a prototype PVT-collector that was built for the single cover sheet-and-tube collector indicated that experimental results were in good agreement with the model predictions which already discussed in numerical models section. For a domestic hot water system the best thermal and electrical annual yield was obtained for the channel-above-PV design, the two-cover sheet-and-tube and Two-absorber PVT-collector insulated type, whereas the electrical performance of these three systems was somewhat lower. The channel-below-transparent-PV design gave the best efficiency, but since the annual efficiency of the PV-on-sheet-and-tube design in a solar heating system was only 2% worse while it was easier to manufacture, this design was considered to be a good alternative [26].

In order to quantify the efficiency of a combi panel, an experimental prototype was built at the Eindhoven University of Technology (Fig. 9) [44]. This was a non optimised first prototype, which was built in order to be able to validate the simulated values generated by the models under study which already mentioned in simulation section [37]. The efficiencies at zero reduced temperature were 0.59 ± 0.015 for combi-panel without electricity and 0.54 ± 0.015 for combi-panel with electricity.

The design of a novel building integrated photovoltaic/thermal (BIPVT) solar collector (Fig. 10) was theoretically analyzed through the use of a modified Hottel–Whillier model [45] and was validated with experimental data from testing on a prototype BIPVT collector [27]. The results showed that key design parameters such as the fin efficiency, the thermal conductivity between the PV cells and their supporting structure, and the lamination method had a significant influence on both the electrical and thermal efficiency of the BIPVT. Furthermore, it was shown that the BIPVT could be made of lower cost materials, such as pre-coated color steel, with-

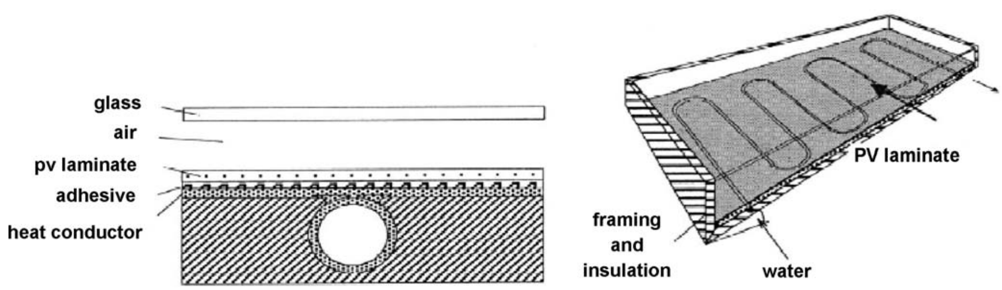
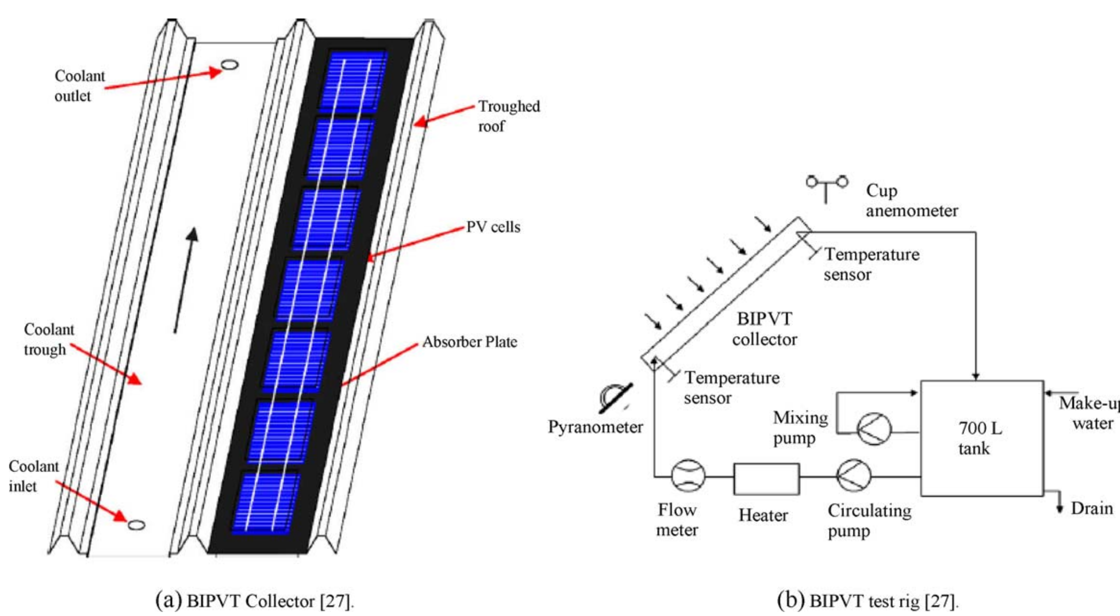


Fig. 9. PV/T thermal collector [44].



(a) BIPVT Collector [27].

(b) BIPVT test rig [27].

Fig. 10. (a) BIPVT Collector [27]; and (b) BIPVT test rig [27].

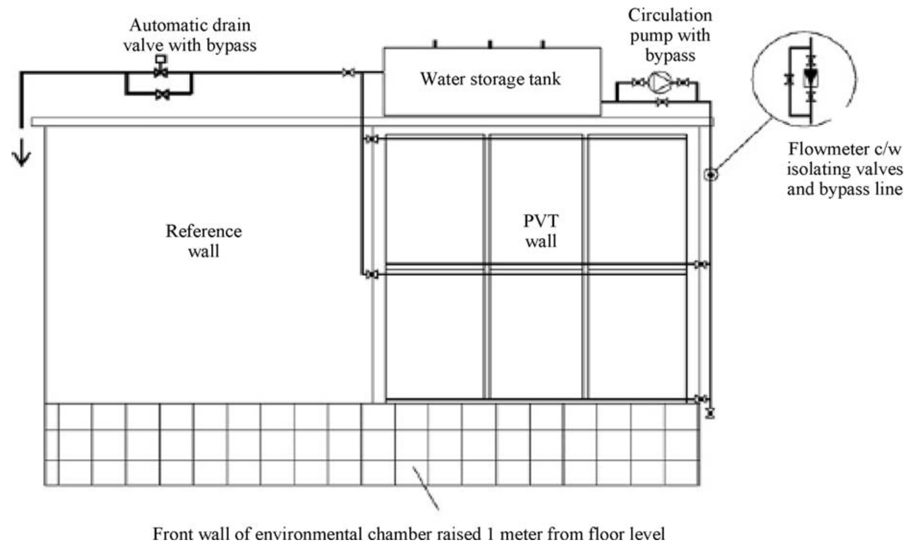


Fig. 11. BiPVT experimental set-up: Schematic diagram of water-heating circuit [46].

out significant decreases in efficiency. Finally, it was shown that by integrating the BIPVT into the building rather than onto the building could result in a lower cost system. This was illustrated by the finding that insulating the rear of the BIPVT may be unnecessary when it is integrated into a roof above an enclosed air filled attic, as this air space acts as a passive insulating barrier.

An experimental study of a centralized photovoltaic and hot water collector wall system that can serve as a water pre-heating system (BIPVT) system was conducted (Fig. 11) [46]. The environmental chamber was placed at the external walls which had the highest space heat gain through the front wall. All internal walls of the test cells were thermally insulated. The main air-conditioning provisions included air-cooled chiller, fan-coil units, and electrical re-heaters. While the cooling coils were fully open, the final control of air temperature in the environmental chambers was by means of the re-heaters, which were able to maintain all inner/outer chambers at the pre-set temperature of $22 \pm 0.5\,^{\circ}$C throughout the year. The heat transmission through the internal walls and the floor slab was negligible. The PV/T wall was consisted of PV/T collectors mounted on the brick wall and water storage tank was located at the roof of the environmental chamber. The experimental results were chosen to study the heat gains (in accordance with space cooling loads) across the PV/T wall as compared to the reference wall in the peak summer period and the cooling load patterns compared between the PV/T wall and the reference wall in winter. The results showed that the PV/T wall reduces the air-conditioned load and the space thermal loads can be much decreased in summer and winter. The thermal efficiency was found 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56%, during the late summer of Hong Kong.

An integrated combined system of a photovoltaic (glass–glass) thermal (PV/T) solar water heater of capacity 200 l designed and tested in outdoor condition for composite climate of New Delhi. [31]. The following parameters were measured hourly during the experimentations: Inlet temperature, outlet temperature, tank water temperature, ambient temperature, collector temperature, module temperature, total and diffuse solar intensity on collector, total and diffuse solar intensity on module, load current and load voltage, Short circuit current and open circuit voltage. The parameters haved also been measured by varying the mass flow rate of water from 0.045 kg/s, 0.06 kg/s and 0.09 kg/s. It was observed that there was a good agreement between theoretical values and experimental values of experimental set-up. The gain and loss factor obtained for the design (30.56% covered with PV module) of system were 0.64 and 5.18, respectively.

A building-integrated photovoltaic and water heating system introduced and the corresponding dynamic simulation model described [39]. The validity of the simulation model was demonstrated by comparing its predicted system operating conditions and derived daily efficiencies with the experimental data sets that fully covered the summer and winter periods, as well as the thermosyphon and pump operated modes. Other than the electrical performance which affected by the on-site shading problem, the outputs from the model showed good compliance with the experimental observations.

A photovoltaic–thermosyphon collector with rectangular flow channels presented (Fig. 12) and the energy performance discussed [33]. An aluminum-alloy flat-box type PVT collector was constructed, with its fin efficiency approaching unity. Its design was primarily for natural circulation and for domestic water heating purpose. The results showed that a high final hot water temperature in the collector system can be achieved after a one-day exposure.

A water-type hybrid collector with polycrystalline PV module on a flat-box type aluminum-alloy thermal absorber was constructed and tested [47]. The test results on the energy performance were very encouraging. The daily thermal efficiency was found around 40%, which was about 0.8 of that for a conventional solar thermosyphon collector system. The energy saving efficiency was found above that of the conventional system. A high final water-temperature in the storage tank could be achievable after a one-day exposure. This made the product design a good potential for serving the domestic market.

A flat-box Al-alloy solar (Fig. 13) PV/T water heating system was designed with natural circulation and experiments were conducted with different water masses and different initial water temperatures in an outdoor environment [42]. As the hot-water load per

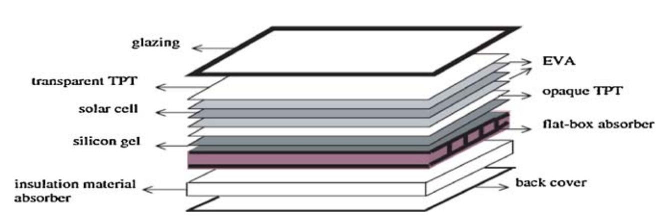


Fig. 12. Constituent layers of the PVT collector [33].

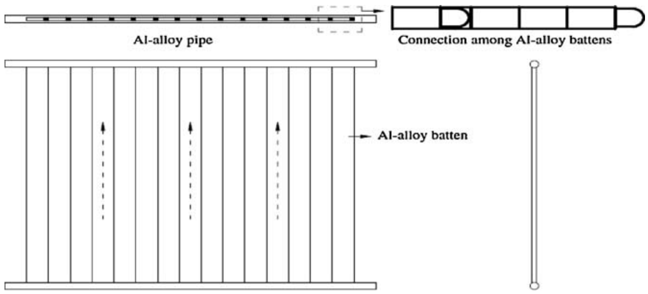


Fig. 13. Construction of flat-box Al-alloy absorber plate [42].

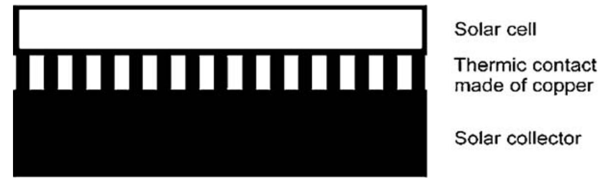


Fig. 14. A scheme of the interface between photovoltaic panel and solar heat collector [49].

unit heat-collecting area exceeded 80 kg/m^2, the daily electrical efficiency was about 10.15%, the characteristic daily thermal efficiency exceeded 45%, the characteristic daily total efficiency was above 52% and the characteristic daily primary-energy saving was up to 65%, for this system with a PV cell covering factor of 0.63 and front-glazing transmissivity of 0.83.

A Fresnel concentrator and a PV/T collector designed using water as the working fluid. The collector, according to Zondag et al. [26], could be classified as a channel PV/T collector with the channel underneath the concentrating opaque PV cells [48]. Experimental results were encouraging because the thermal performance of the solar system gave values above 60%.

A prototype of the optimized panel for the hybrid PV/thermal system was made, using the metallic substrate covered with thin insulating layer [49]. The prototype panel made proved to serve this purpose, giving an efficient cooling of the photovoltaic panel by the collector and demonstrating the 10% increase of the power generated by the panel due to its thermal contact with the collector in the hybrid system. To provide the best possible thermal contact between the panel and the collector, the authors made for each case a special interface made of Cu radiator pressed from one side to the PVP (directly to the substrate material having the PV cells on its other side, to be exact) and to the solar collector from the opposite side, as it is shown in Fig. 14.

The conclusion was that the PVP for application in a hybrid system needs a special design providing efficient heat extraction from it.

Hybrid photovoltaic/thermal water and air based solar systems experimentally studied in outdoor conditions [50]. It was found that PV/T water type system was more efficient than that of the simple mode of air circulation. Furthermore, in term of system performance, it was concluded that by the use of an additional glazing to increase thermal output, a booster diffuse reflector to increase electrical and thermal output, or both, giving flexibility in system design was suitable for improving performance [51].

4.1.3. Case studies in Malaysia

Table 2 summarizes some of the selected previous studies of PV/T water based collectors in hot and humid climate of Malaysia.

5. PV/T hybrid water/air collectors

A solar cell panel for electricity generation, and air/water was made to flow in a duct placed below the surface on which the solar cells were mounted to extract heat from the system, thereby cooling the cells and increasing their efficiency theoretically studied [57]. The mathematical model developed for predicting the performance of the system was based on energy balance equations written for the various nodes of the system. The temperatures of the solar cells and of the outlet fluid as a function of time predicted.

An analytical expression for the temperature of solar cell and water and an overall thermal efficiency of integrated photovoltaic and thermal solar (IPVTS) water/air heating system derived as a function of climatic and design parameters [58]. Four configurations, namely (a) unglazed with tedlar (UGT), (b) glazed with tedlar (GT), (c) unglazed without tedlar (UGWT) and (d) glazed without

Table 2
Summary of some of the selected previous researches in Malaysia.

Type of cells	Performance studies		Performance results		Remarks	Ref.
	Experimental work	Simulation studies	Thermal efficiency	Electrical efficiency		
Polycrystalline silicon		√	50.12%	11.98%	Seven new design configurations of absorber collectors were designed, investigated and compared (Fig. 15). Based on these simulations, spiral flow design (f) proved to be the best design	[52]
Amorphous silicon		√	72%	5%	A design concept of water-based PVT collector for building-integrated applications has been designed and evaluated. The results of simulation study based on the metrological condition of Malaysia for one day in the middle of March; 2009. ambient temperature was between 22 and 32 °C and fluid flow rate of 0.02 kg/s	[53]
Polycrystalline silicon Amorphous silicon		√	51% 72%	11.6% 5%	This work shows the results of performance simulation study of a-Si and c-Si photovoltaic/thermal (PVT) solar collector in tropical climate such as Malaysia. The results showed that at solar radiation between 700 and 900 W/m^2, ambient temperature between 23 and 34 °C and fluid flow rate of 0.03 kg/s, the highest thermal and electrical efficiency obtained (Fig. 16)	[54,55]
Monocrystalline silicon		√	–	–	The results indicates that increasing collector area from 1 m^2 to 10 m^2 results in an increase in useful heat gain, electrical power output and solar fraction. However, when collector area is greater than 7 m^2, these improvements are small, especially for useful heat gain	[56]

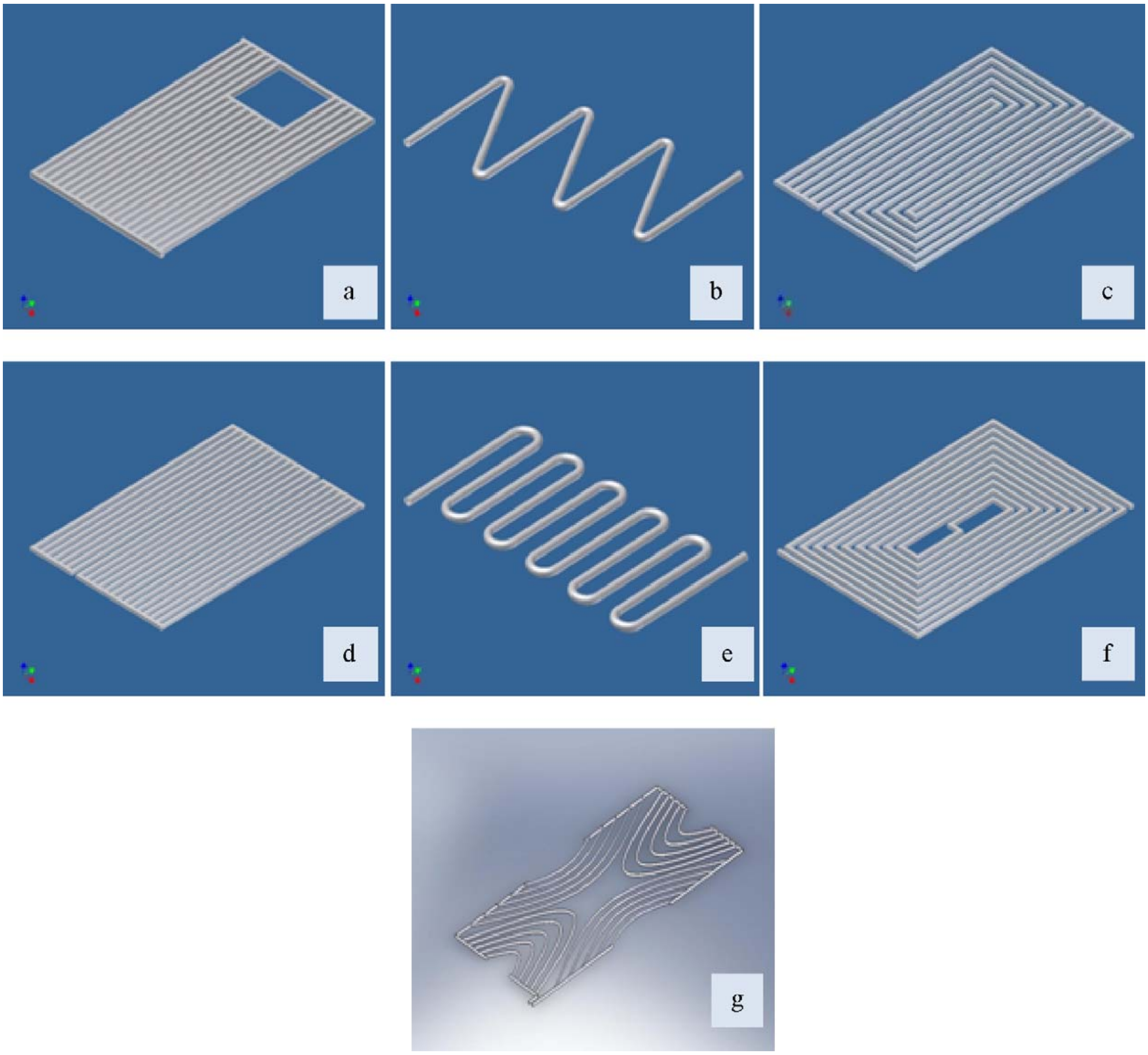


Fig. 15. (a) Direct flow design, (b) serpentine flow design, (c) parallel-serpentine flow design, (d) modified serpentine-parallel flow design, (e) oscillatory flow design, (f) spiral flow design, (g) web flow design [52].

tedlar (GWT) considered. Comparison of the IPVTS system with water and air heater had also been carried out. It is found that:

1. the case (c) gives better performance at lower operating temperature;
2. the glazed with tedlar gives better performance at high operating temperature;
3. the IPVTS system with water as working fluid gives better performance except glazed without tedlar, i.e. case (d).

A new concept of photovoltaic/thermal (PV/T) collector (Fig. 17) which combined preheating of the air and the production of hot water in addition to the classical electrical function of the solar cells presented [59]. A mathematical model of the PV/T bi-fluid hybrid collector presented for a forced ventilation of the air gap and a laminar water flow. The experimental study carried out validates the values obtained during simulation, which were used in conceiving the final design of the prototype. A parametric study permitted the trends in the variation of the temperature of cells and the fluids as a function of water and air mass flow rates and the collector length to be determined. The solar collector performance study indicated that for the specific collector length and mass flow rate, the thermal efficiencies were able to reach approximately 80% and the estimation of electrical efficiency indicated that the cooling of the PV cells was satisfactory but could be improved. The simulation results showed that the prototype was appropriate for domestic hot water production and for some solar cooling applications.

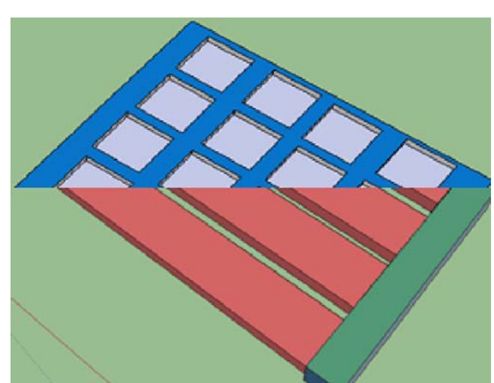


Fig. 16. Absorber plate and PV module [54,55].

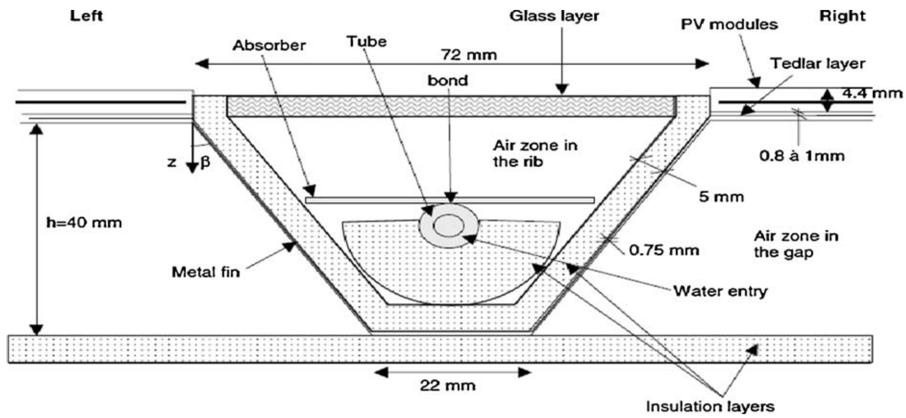


Fig. 17. Cross section of the PV/T hybrid bi-fluid collector [59].

A new type of PV/T collector with dual heat extraction operation, either with water or with air circulation presented [60]. Experiments with dual type PV/T models of alternative arrangement of the water and the air heat exchanging elements were performed. Three alternative modes of placing the water heat exchanger inside the air channel were tested. In the first mode the water was placed in thermal contact with the back surface of PV module and the air heater exactly after it, forming also the thermal insulation envelope (MODE A). In the second mode the air heater was placed directly on the PV module back and the water inside the formed air channel (MODE B). In the third mode the air mounted directly on the back of PV module and the water was attached at the opposite air channel wall (MODE C). The results showed that the water heat exchanger positioned at the PV rear surface gives the best results for combined water and air heat extraction.

6. Other type of liquid PV/T collectors

A single-junction crystalline silicon photovoltaic, a triple-junction amorphous silicon photovoltaic integrated with roofing materials, and a flat plate solar collector by circulating brine at a low energy house at Hokkaido University studied (Fig. 18). It was clarified the feasibility of the solar energy utilization systems [61].

1. Experiments under constant supply temperature of brine were made and it was found that conversion efficiency ranged from 10% to 13%, and that collector efficiencies at 20 and 40 °C brine temperature were from 40% to 50% and approximately 20%, respectively.
2. The efficiency of the hybrid solar collector was compared to those of a photovoltaic and a solar collector and it was clarified that the hybrid collector had an advantage in terms of exergy efficiency, though there is some lowering of collector efficiency.
3. Total energy efficiency and exergy efficiency of the solar energy utilization systems were analyzed. The total energy efficiency of hybrid solar collector was roughly equivalent to that of solar collector, and the total exergy efficiency was the highest of the three systems. The hybrid system was expected to reduce panel installation area by approximately 27%.
4. Field measurements were carried out from November 1998 to October 1999 at a low energy house at Hokkaido University. Except for winter, the mean conversion efficiency of array and the collector efficiency were stable at 8–9% and 25–28%, respectively. The dependency on solar energy was 46.3%.

7. Economic analysis of PV/T water collectors

The economic study of a solar domestic hot water system in Kuwait based on current PV module prices as provided by the manufacturer, as well as the current prices of conventional fuel sources in Kuwait proposed [62]. The economic calculations were based on the life cycle savings method developed by Brandemuehl and Beckman [63]. Oil prices in the range of US$20–30 per barrel were studied. At the prices of photovoltaic modules in 2002 and a low oil price, photovoltaic-powered solar water heating systems were found to be economical.

A life cycle analysis was performed in order to obtain the total cost (or life cycle cost) and the life cycle savings of a hybrid PV/T solar system for domestic hot water and electricity production [5,9]. The economics of the systems considered showed that for locations with higher available solar radiation, the economics gave better figures. Also, although amorphous silicon panels were much less efficient than the polycrystalline ones, they gave better figures due to their lower initial cost, i.e., they had better cost/benefit ratios.

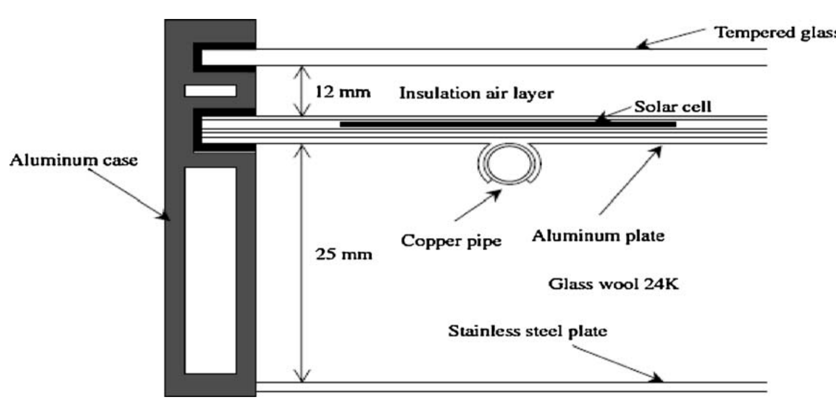


Fig. 18. Cross-section of hybrid solar collector (single-junction crystalline silicon type) [61].

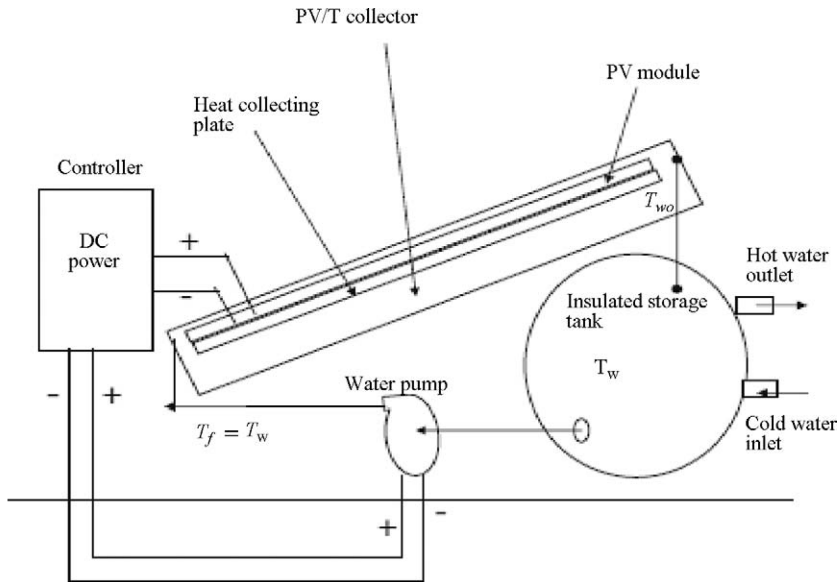


Fig. 19. Schematic diagram of an integrated PV/T system (IPVTS) [66].

The economic analysis of the a hybrid photovoltaic–thermal solar energy system was performed by considering the extra cost required to modify the PV modules and the other equipment required for the construction of the hybrid system, against the extra energy benefit obtained by the modified system, i.e., extra electrical energy above that obtained from a non-hybrid PV module and the thermal energy output [35]. The results showed that the life cycle savings of the system were Cy£790.00 and the payback time was found to be equal to 4.6 years.

8. Performance analysis of PV/T collectors using energy and exergy analysis methods

A photovoltaic thermal collector consisted of liquid heating flat-plate solar collector with mono-Si PV cells on substrate of non-selective aluminum absorber plate designed and constructed [64]. From the annual experimental evaluation based on exergy, it was concluding that:

1. The PV/T collector can produce higher output density than separate PV module or liquid heating flat-plate collector.
2. The higher energy gain achieved by a single-covered PV/T collector and the worst performance was by a PVmodule.
3. Using exergetic evaluation, the best performance was found to be that of the coverless PV/T collector, the second to be the PV module and the third to be the single covered PV/T collector and the worst to be the flat-plate solar collector.
4. The coverless PV/T collector produced 8% more electrical energy than the PV module, and a single panel of the single-covered PV/T collector produced both electrical and thermal energy in amounts as large as the PV module and the flat-plate solar collector.

The flat plate collectors partially and fully covered by PV module considered [65]. A detailed analysis of energy, exergy and electrical energy presented and it was observed that the collectors partially covered by PV module combined the production of hot water and electricity generation and it was beneficial for the users whose primary requirement was hot water production and collectors fully covered by PV was beneficial for the users whose primary requirement was electricity generation. Annual thermal and electrical energy yield was also evaluated for four different series and parallel combination of collectors for comparison purpose considering New Delhi conditions.

An analytical expression for the water temperature of an integrated photovoltaic thermal solar (IPVTS) water heater (Fig. 19) under constant flow rate hot water withdrawal obtained [66]. It was observed that the daily overall thermal efficiency of IPVTS system increases with increase constant flow rate and decrease with increase of constant collection temperature. The exergy analysis of IPVTS system also carried out. It was further to be noted that the overall exergy and thermal efficiency of an integrated photovoltaic thermal solar system (IPVTS) was maximum at the hot water withdrawal flow rate of 0.006 kg/s.

Based on experimental data and validated numerical models, a study of the appropriateness of glass cover on a thermosyphon-based water-heating PV/T system was carried out [67]. The exergetic efficiency of the unglazed condition found better than the glazed condition in specific ranges of six operating parameters, namely, cell efficiency, packing factor, ratio of water mass to collector area, solar radiation, ambient temperature, and wind velocity. Hence, if the design target was to acquire either more electrical energy or more overall energy output in "quality", the second law efficiency was then more appropriate for the assessment.

9. The direction of water and refrigerant based PV/T systems—future research and development

PV/T Solar system may not yet improve enough for cost effective commercial applications, if they just consider for one application. It is economic to utilize integrated PV/T systems to provide more than one application, simultaneously or independently.

Direct production of services hot water is more practical than generating warm air for space heating in PV/T applications. Therefore, many studies have been conducted extensively in this field and water based PV/T collectors and systems for hot water production have been applied in a wide range of buildings such as domestic building, school, factory, hospital and hotel, especially in hot and humid climate which space heating is less required except for some specific conditions and buildings like: hospitals and hotels. In PV/T hot water production areas, consideration should be taken into account in making the systems ready in order to provide multi-functional services such as water heating, space heating and cooling simultaneously. Thus, it makes the system energy efficient and the

cost of multi application mode system would be less than the cost of separate systems [68].

Solar and PV/T air cooled collectors have already been used for drying products in solar dryer and solar assisted heat pump drying technologies, but any application of PV/T water based drying systems have not been reported yet. However it can also be used in the future. It is possible to design solar dryer systems which employ water cooled PV/T collectors. Moreover, the incorporation of the other applications such as water heating, space heating and cooling, pool heating or process heating enable to improve the economics of these systems more and recover heat that would otherwise be rejected to the atmosphere. Research works should be carried out in this area for investigating the effects of using PV/T water based on improving the Coefficient of Performance (COP) of dryer and multifunction systems.

A water-based PV/T system is able to achieve a higher overall energy output per unit collector area than the “side-by-side” systems. However, for daily operation the photovoltaic efficiency of the hybrid system still will drop considerably towards the end of the day, when the heat removal fluid (water) temperature in the storage tank will finally reach the level that meets the hot-water demand requirements. In addition, if the evaporating refrigerant of a heat pump is used as the coolant of the PV cells, a lower operating temperature and accordingly a higher PV efficiency can be achieved [10]. Most solar energy processes require an auxiliary (i.e., conventional) energy source. Hence, solar assisted system includes both solar and conventional equipment (combining PV/T collector and heat pump) is a very promising and attractive concept. It is able to eliminate many difficulties and disadvantages of using solar systems or solely using heat pump drying separately and the annual loads are met by a combination of the sources [69].

10. Conclusions

The results of the some studies have been conducted on water cooled PV/T systems and few studies of PV/T-SAHP systems have been conducted. A brief overview of the some researches on liquid cooled (water and refrigerant) PV/T systems shows outlook and restriction of the technology. In order to get more power and heat from PV/T system, it is necessary to cool the PV cell and decrease its temperature, that it is not an easy task especially in hot and humid climate areas. There is sometimes a lack of an effective cooling strategy of PV/T panels while ambient temperature during day starts to go up. The water based photovoltaic thermal collector systems are practically more desirable and effective than air based systems under meteorological conditions of these climates due to innate nature of water.

There is a promising future to couple solar PV technology with solar thermal technology which takes advantage of water for cooling the PV cells in order to utilize the solar radiant energy within a much larger wavelength spectrum especially for BIPVT and drying applications. There are several ways to make PVT water based technology more promising with the advent of newly designed and developed thermal absorber. It is important to note that, very few studies are available regarding utilization of PV/T water based system applications in space cooling, heating and nearly no researches related to using this type of PV/T absorbers for drying, however a lot of comprehensive investigations have been developed for using PV/T water heating systems; therefore further attempts should be conducted in this field and the integration of combined PV/T water cooled technologies into the heating and cooling systems might be much more developed and multi-functional systems should be improved to make these systems economic.

The results of few studies of PV/T-SAHP systems indicated that the COP of this systems can be much better than that of conventional heat pump and also both PV and phototermic efficiency have been improved, but due to the fact that few studies have been conducted in this area, further experimental and numerical work should be carried out aiming at incrementing our knowledge regarding improving COP of heat pump, electrical performance and thermal efficiency of PV solar collector using PV/T heat pumps.

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